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A Determination of Reflectivity of Opaque Ore Minerals with a Weston II Light Meter

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A DETERMINATION OF REFLECTIVITY OF OPAQUE ORE MINERALS WITH A WESTON II LIGHT METER

by
LOUIS L. BERGAN

A Thesis
Submitted to the Department of Geology
in Partial Fulfillment of the
Requirements for the Degree of
Bachelor of Science

MONTANA SCHOOL OF MINES
Butte, Montana
May 13, 1951

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ABSTRACT

Measurements of reflectivity of opaque ore minerals can be made with the common photographic light meter and a standard reflecting microscope, both of which are available to most Geology laboratories. During the course of the investigation, approximately 30 minerals were examined, of which 10 were duplicates. Comparable results, for the most part within 3% of previously determined values, were obtained.

Absolute values of percentage reflection were obtained by assigning a specific value (54.5%) on an arbitrary scale to pyrite and using it as a standard to which all other reflectivities were compared. The reflectivity of the various minerals appears to be determined by the following factors:

1. the index of refraction (according to the Fresnel equation)
2. the molecular refractivity (according to the Lorenz-Lorentz equation)
3. the atomic number (as modified by the position on the periodic table and the atomic volume)

These factors are all discussed in the body of this report and the results of the experimentation are presented in both tabular and graphic form.

DETERMINATION OF REFLECTIVITY OF OPAQUE ORE MINERALS WITH A WESTON II LIGHT METER

INTRODUCTION

Recent technological advances have improved the sensitivity of ordinary photographic light meters to the extent that their use is justified in measuring the reflectivity of light from polished surfaces of isotropic and opaque ore minerals. Such a measurement has been found to be constant for each particular mineral in the same manner that the index of refraction is a constant for the non-opaque minerals. (5: 425)

However, the procedures as described in the literature involve the use of rather special types of equipment that are not readily available in most geological departments. Hence, these techniques as described are of little value, unless the necessary equipment is available. If commonly available equipment could be used, then this procedure might become a handy "tool" for mineral identification. The writer chose as a thesis, to investigate the problem of using a common photographic light meter, and a student model reflecting microscope, to determine the reflectivity values of the common opaque minerals, and to determine if the values corresponded to those given in previously published reports.

In an undertaking such as this, it is often required to call upon knowledge and experience other than one's own. The understanding advice and cooperation of David S. Gleason, Donald W. McGlashan, Edwin G. Koch, Eugene S. Perry, Forbes S. Robertson, Loretta Buss Peck, and Stephen W. Nile have facilitated the preparation of this report.

PREVIOUS WORK

Considerable research on the subject of the reflection of light by opaque polished ore surfaces has been undertaken by scientists in various parts of the world. The initial studies of Drude and others provided the impetus necessary for further investigation. The work of Drude was followed by intensive analysis of the problem by Schneiderhohn and Ramdohr in Germany and Orcel and co-workers in France. (13: 76) The hypothesis that the measurement of reflectivity would provide numerical constant to aid identification of isotropic minerals was confirmed.

Notable contributions since 1933 have been made by Phillips (12), Folinsbee (5), and Moses (10). The most complete study was completed by Moses (10) on a selected suite of minerals polished by the Harvard Process.

The trend of past investigations can be divided into two categories:

1. Photometric methods.--Relative values of reflectivity are obtained by varying and controlling the field of light by means of a prism photometer.

2. Photoelectric methods.--By means of a photoelectric cell, the actual intensity of the light reflected from the mineral can be measured and compared with a measurement made on a standard mineral whose reflectivity is already known. (13: 77)

The main objection to a measurement of reflectivity as a means to identification, as pointed out by Short, (13: 77), "...is that two minerals of widely different chemical composition may have reflectivity values within 1 percent of each other." It follows that the method must be used in conjuntion with other methods if positive mineral identification is desired.

THEORETICAL CONSIDERATIONS

Dr. J. Orcel of Paris is credited with the first application of Einstein's quantum theory to the determination of reflectivity. This theory, simply stated, is as follows: the total energy of the current produced is equal to the total energy of light from emission minus the energy required to separate the electrons. (13: 83-86)

Only certain substances, however, such as metallic sodium, cuprous oxide, and selenium salts possess the ability to develop electron potential when exposed to light. In other words, there is a transformation of light energy into electrical energy. Photoelectric cells, such as the Weston light meter used in this investigation, utilize this principle of operation and generate electricity without benefit of additional outside current.

Reflectivity expressed in decimal form may be calculated from the Fresnel equation for isotropic transparent substances.

$$R = \frac{(n-1)^2 \; nk^2}{(n-1)^2 \; nk^2}$$

where n is the index of refraction of the mineral and k is the index of absorption. Phillips (12: 459) states that the absorption index of the sulphides is of secondary importance in determining reflectivity, because, in the strictest sense, it is not true metallic reflection and is due mainly to high refractive indices. He further considers that mineral surfaces of these types can be considered as transparant in thicknesses so small that they are large compared to the wave length of the light used. Neglecting the

absorption factor, the equation becomes:

$$R = \frac{(n-1)^2}{(n-1)^2} \qquad (5: 427)$$

Plate I presents the curve showing the calculated reflectivity derived from the above equation. For comparison, the actual values obtained by the author are plotted on the same graph by circles. The indices of refraction have been determined for only eight of the twenty minerals used, therefore the values plotted represent only a portion of the series.

The observed values fall below and to the right of the calculated curve. Phillips (12: 428) explains the horizontal deviation as the result of neglecting the absorption factor in the use of the formula.

The indices of refraction used to plot the observed values were determined for lithium light. Folinsbee revised his curve downward to obtain comparable values for white light but did not state by what method he accomplished it. The author, utilizing the Hartman formula:

$$\lambda = \lambda_0 + \frac{C}{n - n_0}$$

found the change in n (index of refraction) with a change in wave length from 6712A to 5500A to be 0.25. The calculated and revised curves are both shown on the graph. (Plate I)

If the Fresnel equation is revised and solved for "n" (index of refraction), and this value substituted into the Lorenz-Lorentz relationship; the molecular refractivity may be determined thus:

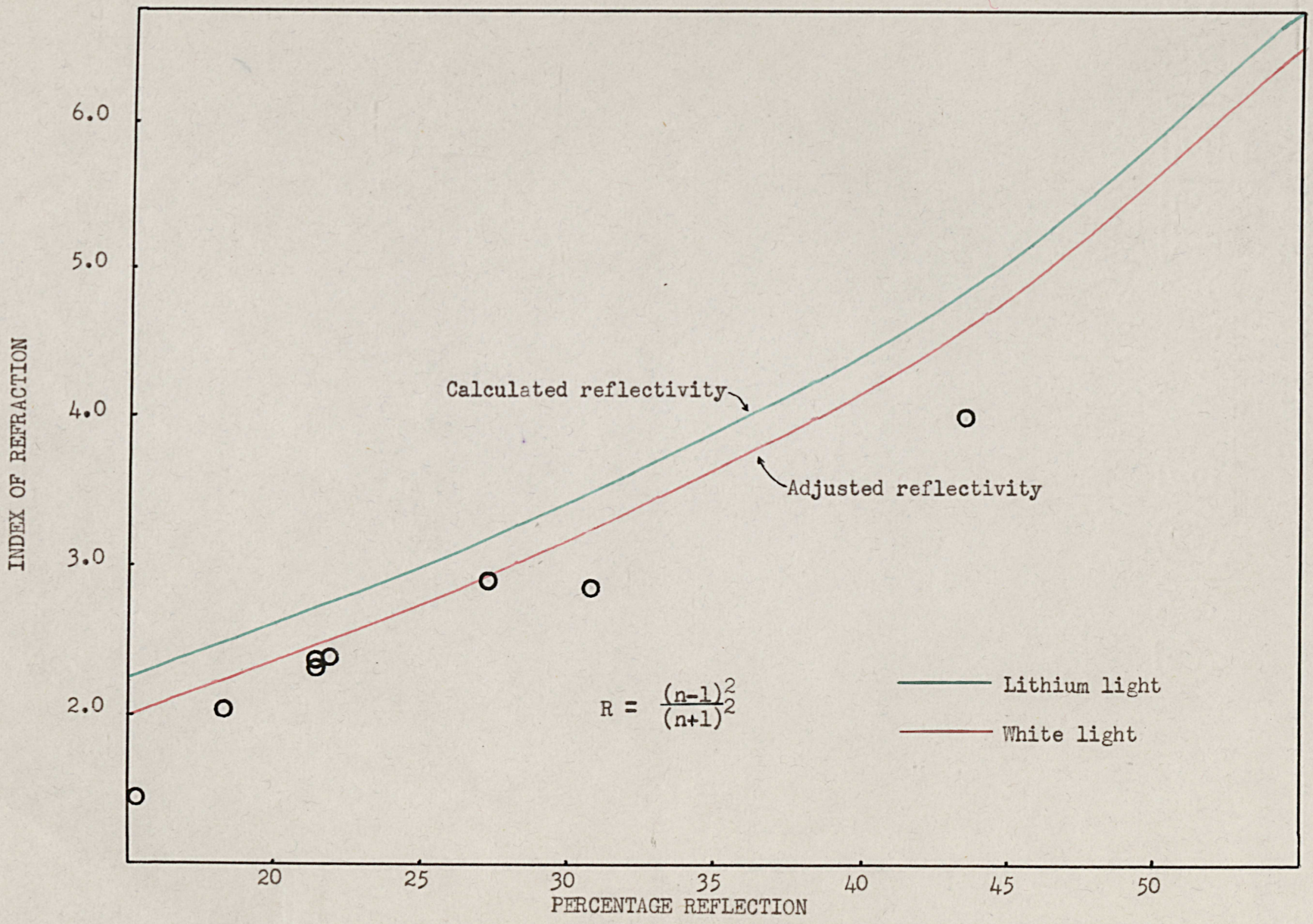

PLATE I The relation of calculated reflectivity to observed reflectivity plotted as circles.

$$MR = \frac{M\ (n^2-1)}{d\ (n^2-2)}$$

Phillips states that an "additive relationship" was found to hold for series of minerals over a wide range of molecular weights and reflectivities. (12: 460) The "additive relationship" was interpreted by the author as an increase in molecular refractivity with increasing molecular weight. The relation between these two factors is graphed in Plate II. All molecular weights, densities, and indices of refraction used in the calculations, along with the resulting values can be found in Table No. 1.

Phillips (12) points out that a determination of this kind can be utilized in two ways: (1) as a method of computing reflectivity, and (2) as a useful check on the density values quoted in literature. Refractivity values (MR) derived by using the above mentioned equation should be additive in any of the crystal systems in which the electron-shells are not deformed. Any departure from the additive sequence should be interpreted as a deformation of at least one of the constituents. (12: 461)

Phillips also noted an increase in reflectivity amongst the simpl e sulphides, selenides, and tellurides with increasing atomic number. This relationship was checked by the author. Further discussion is contained in the latter part of this paper.

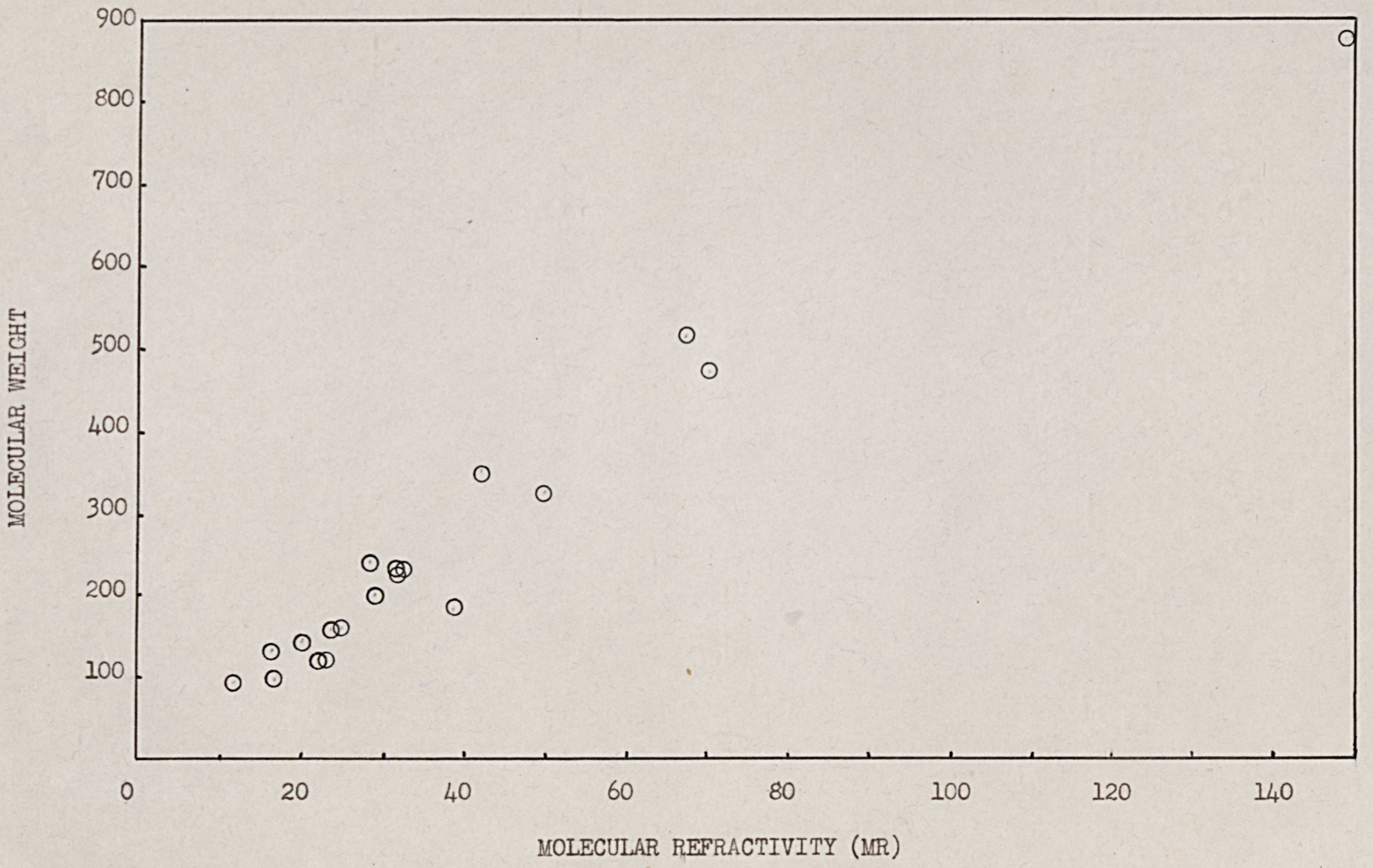

PLATE II. The relation of the molecular weight to the molecular refractivity as calculated for the twenty minerals listed in the appendix.

THE EXPERIMENTAL DETERMINATION OF REFLECTIVITY

Apparatus

The following items comprise the entire list of articles that were used to conduct this series of experiments and are shown in Figures 1 and 2, Plate III.

1. Spencer reflecting microscope (American Optical Co.)
2. Weston Master II light meter
3. Universal Microscope Lamp No. 353 (American Optical Co.)
4. Adaptor (for holding light meter to microscope)
5. Polished specimans (1 mm.^{2} scratch-free)
6. Blue filter, large hand lens, black cloth, and chamois polishing block.

The Weston Master II light meter was utilized in the entire set of experiments and seemed to give very satisfactory results when a simple, linear scale, graduated from 0 to 100, was constructed from graph paper (circular) and superimposed over the original scale. This scale was read to the nearest 0.1 percent.

The Universal Microscope Lamp No. 353 met the requirement for a light source of constant color quality and intensity successfully. This lamp is equipped with a three-link jacknife standard and base, a clear glass bulb, and a transformer that cuts line voltage down to 6.5 volts and permits a current of 2.75 amperes to pass through the lamp. The triple lens condensing system is in a spiral focusing mount and is capable of condensing enough light to register values of over 50% on the linear scale that had been constructed. Very little voltage variation was noticed when conducting experiments with a magnification of 240. When using higher magnifications,

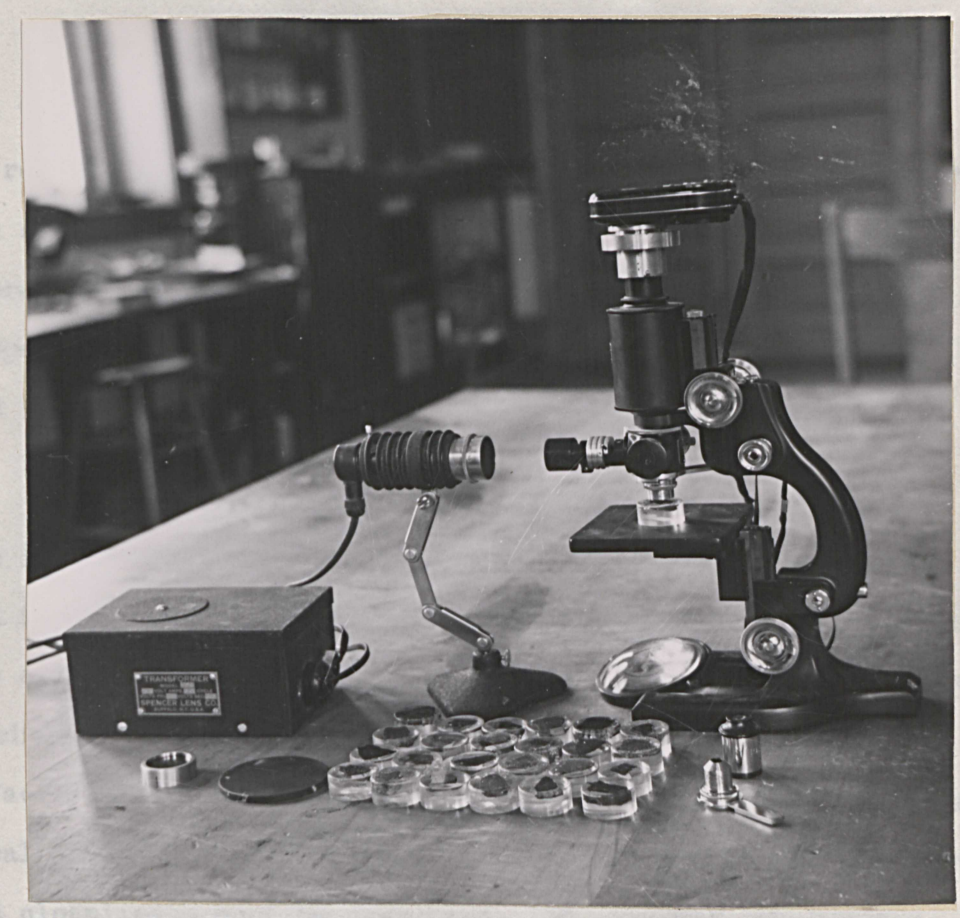

Figure 1. The Reflection Apparatus in Operating Position

Figure 2. The Brass Adaptor

PLATE III

however, the fluctuation was distinctly noticeable. In this case, several readings were taken over a period of time, the mean average of which constituted the final value recorded.

A brass adaptor provided a light-proof connection between the microscope and the light meter. More detailed information may be obtained by referring to Figures 1 and 2, Plate III.

Preparation of the Specimans

The specimans used during the course of experimentation were obtained from the Economic Geology laboratory of the Montana School of Mines and were polished in a Graton-Vanderwilt Polishing Machine. The grinding and polishing procedure is perhaps the most important single factor in obtaining satisfactory results. Although no unusual mechanical skill is required to operate the polishing machine, extreme care and cleanliness must be exercised. If, however, reasonable precautions are observed, polished surfaces can be obtained that are practically free from relief--of the order of 0.2 microns--and also free of surface flow in the softer minerals, a common feature resulting from the use of cloth laps.

An absolutely scratch-free and pit-free surface 1 mm. in diameter under a magnification of 470X was the goal that was desired. Polish is reported on an arbitrary basis of good, fair, or poor in the Appendix under the title of "Tabulated Data for Experiment No. 1." Although it is extremely difficult to evaluate the perfection of polish for determinations of this kind, a qualitative description may be considered as follows:

> Good--no pits or scratches; Fair--few minor scratches or pits; Poor--many scratches or pits of any nature

Procedure

The light from the microscope lamp was made to pass through a condensing system with diaphragm; reflected down through a vertical illuminator through an 8 mm. objective lens to the mineral surface; then reflected back up the tube of the microscope to the photoelectric cell of the light meter inserted in the position of the ocular.

The initial phase of each experiment consisted of placing a well polished pyrite surface beneath the microscope and obtaining an exact focus upon a scratch-free area. The ocular was removed and the light meter with the adaptor substituted in it's place. Almost perfect alignment of the lamp and the microscope was required to permit satisfactory readings to be taken. After such alignment, however, the value for the pyrite standard was established and the light path was not disturbed during subsequent determinations.

Following the determination of the pyrite standard, a second polished surface was introduced beneath the microscope; the ocular again inserted after the removal of the meter and adaptor. Once this was accomplished, the intense illumination necessary for recording on the meter made impossible visual examination of the speciman, and thus necessitated the insertion of a thick, blue filter between the lamp and the microscope to observe the speciman. Next, the new surface was brought into exact focus by altering the position of the stage on which it rested. Obviously, an adjustment of the microscope tube would have disturbed and altered the collimating system. The final steps consisted of removing the filter, replacing the ocular with the meter and adaptor, and recording the new value registered on the linear scale. This procedure

was followed throughout the experimentation, i.e., repeated for each new mineral surface for which a reflectivity value was desired.

All mineral surfaces were lightly buffed immediately before making a determination to remove any effects of oxidation. It is extremely important that measurements be taken shortly after polishing as oxidation effects have been noticed in as short a time as three hours.

A constant light path was maintained during any one set-up. The light path for different experiments, however, was purposely varied to obtain differing conditions. The reproducability of the results was thus partially checked. It should be repeated that the light path was kept constant for any single series of readings.

A correction for "flare" which results from light reflected off the top of the objective lens must be made. Folinsbee's method, (5: 426) was utilized to determine the amount of flare. The pyrite standard was replaced with a piece of black velvet and the small amount of reflectivity (0 to 6%) registered on the meter was recorded as the amount of flare. If the objective lens was removed the meter reading immediately became zero. A determination for flare must be made for each separate set-up, as the amount of flare varies with the light intensity, type of microscope, magnification, and various objective lenses.

Method of Calculation

The reflectivity of the mineral surfaces was determined by the formula:

$$(M-F)\ k = R$$

where M equals the meter reading, F equals the amount of flare determined for that particular set-up, k equals a constant obtained by dividing 54.5 by the scale reading for the standard pyrite, and R equals the reflectivity. Needless to say, the value of k becomes unity when the light intensity is adjusted to read 54.5 for the pyrite standard.

Values of R obtained by this method are true values of reflectivity expressed in percent, because pyrite has been previously determined to reflect 54.5% of the incident light directed vertically upon its surface. (10) (5)

Complete observations and calculations for each experiment are given in the appendix. Each of these experiments represents values obtained for an entirely different set-up; differing focal lengths, lenses, magnification, standard values, and amount of flare.

Reproducability of Results

The perfection and improtance of the polish has already been stressed in an earlier part of this report, but it may be advantageous to point out that the only comparable results obtained in Experiment No. IV (Appendix) were for those minerals that had good or fair polishes and that the minerals having a relatively poor polish failed by as much as 14% of being comparable with other readings. Other factors must be considered in regard to this particular experiment, however. Poor results can be attributed to any or all of the following:

1. Poor polish
2. Light variation (intensity)
3. Too great a magnification

PHYSICAL AND CHEMICAL CHARACTERISTICS OF POLISHED SURFACES

Mineral Name	Composition	Crystal Habit	Mol. Wt.	Anisotropism
Arsenopyrite	$FeS_2.FeAs_2$	Monoclinic	325.6	S
Bismuthinite	Bi_2S_3	Orthorhombic	514.2	S
Bornite	$FeS.2Cu_2S.CuS$	Isometric	469.5	I-W
Chalcocite	Cu_2S	Orthorhombic	159.2	W
Chalcopyrite	$CuFeS_2$	Tetragonal	183.5	W
Chromite	$FeOCr_2O_3$	Isometric	223.8	I
Covellite	CuS	Hexagonal	95.6	S
Cuprite	Cu_2O	Isometric	143.2	D
Franklinite	$FeMnZn.Fe_2O_4$	Isometric	351.8	I
Galena	PbS	Isometric	239.2	I
Hematite	Fe_2O_3	Rhombohedral	159.7	W
Ilemenite	$FeOTiO_2$	Rhombohedral	199.6	D
Magnetite	Fe_3O_4	Isometric	231.4	I
Marcasite	FeS_2	Orthorhombic	119.9	S
Niccolite	NiAs	Hexagonal	133.6	S
Pyrite	FeS_2	Isometric	119.9	I
Pyrrhotite	Variable	Hexagonal	.....	S
Smaltite	$CoAs_2$	Isometric	228.7	?
Sphalerite	ZnS	Isometric	97.4	I
Tetrahedrite	$Cu_8S_4.Sb_2S_3$	Isometric	883.0	I

TABLE NO. I

PHYSICAL AND CHEMICAL CHARACTERISTICS OF POLISHED SURFACES

Density	Refractive Index	MR Value	Observed "R"	Folinsbee Value
6.05	....	50.0	54.1	52.4
6.78	....	67.0	43.7	41.0
5.15	....	70.0	28.5	23.8
5.65	....	23.4	37.0	32.3
4.20	....	38.6	43.7	43.2
4.44	2.12	32.1	18.4	12-16-26
4.68	1.45	12.0	15.5	15.1
6.00	2.85	20.1	27.3	27.7
5.15	2.36	42.1	17.4	18.9
7.45	4.01	28.4	43.4	42.4
5.10	2.87	24.7	30.7	27.2
4.67	....	29.0	21.1	19.4
5.07	2.42	31.5	21.8	21.1
4.76	....	23.1	50.4	51.5
7.50	....	16.6	53.2	52.6
5.06	....	22.0	54.5	54.5
4.61	....	....	41.1	39.9
6.50	....	32.6	54.5	54.6
4.00	2.34	16.6	21.4	17.8
4.75	....	150.0	32.6	31.2

TABLE NO. I (cont.)

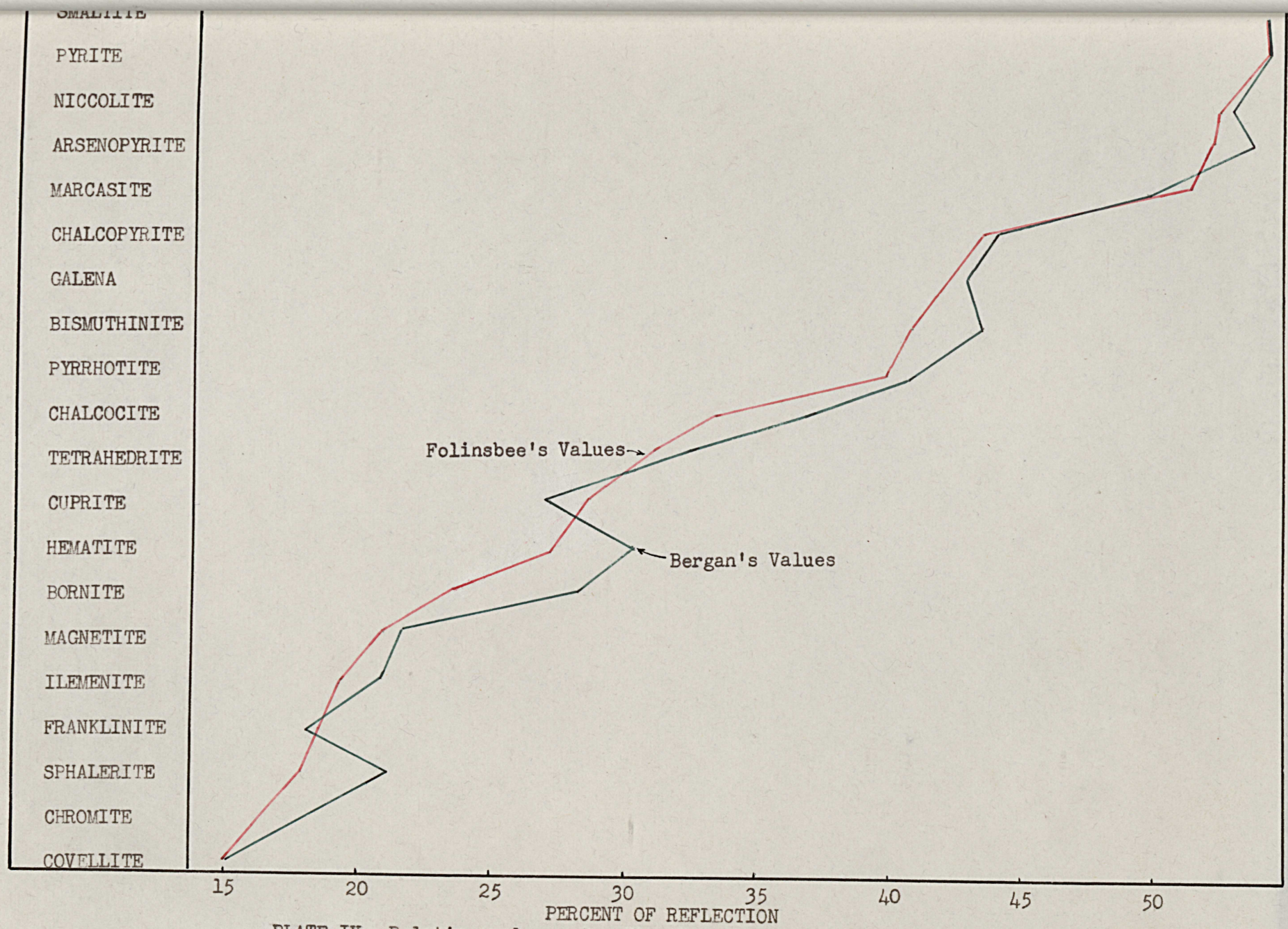

PLATE IV. Relative values of reflection obtained by Folinsbee and Bergan

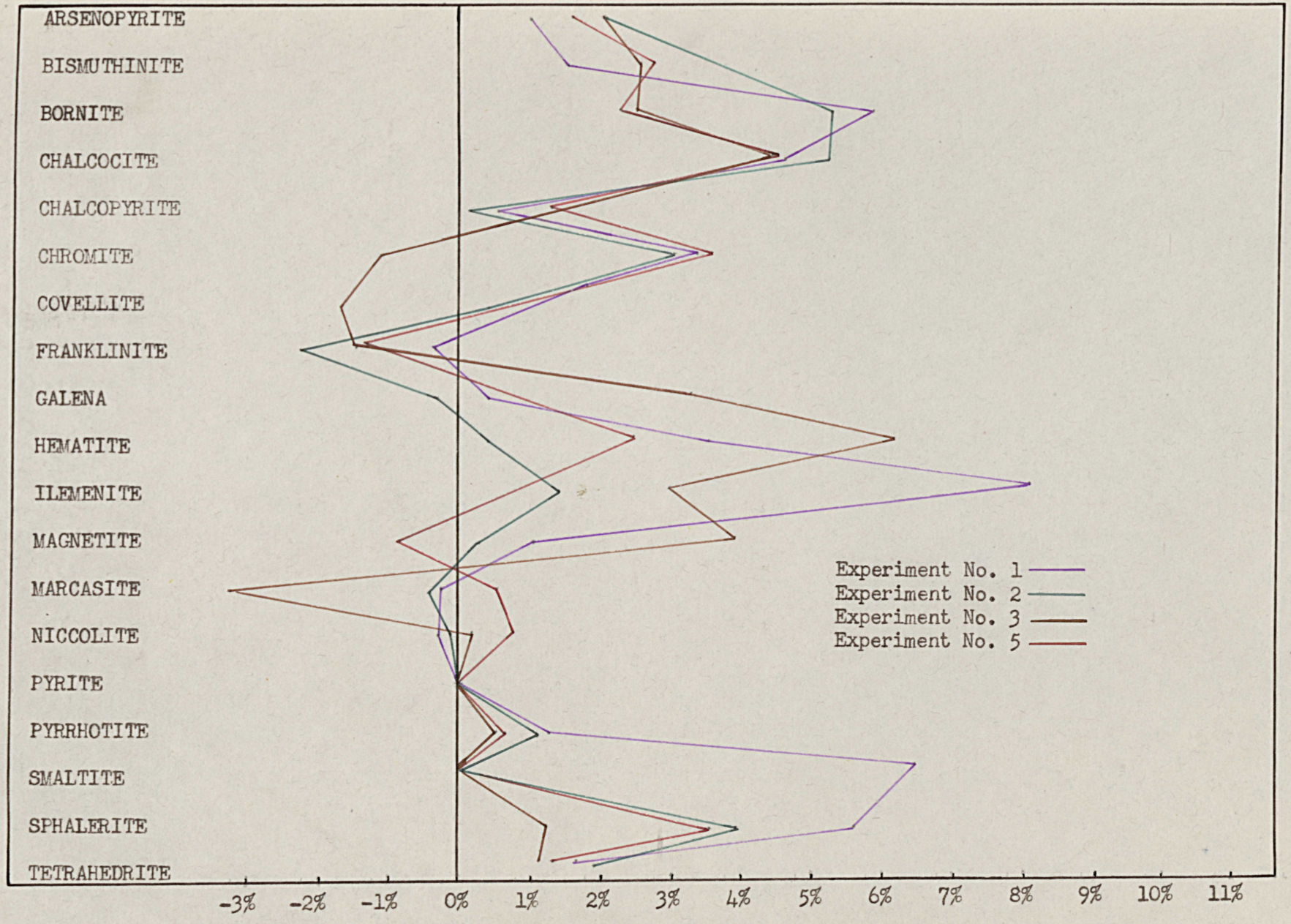

PLATE V. Deviation Chart--Represents the deviation of the author's work from the Folinsbee values of reflectivity which are graphed as the zero percent line.

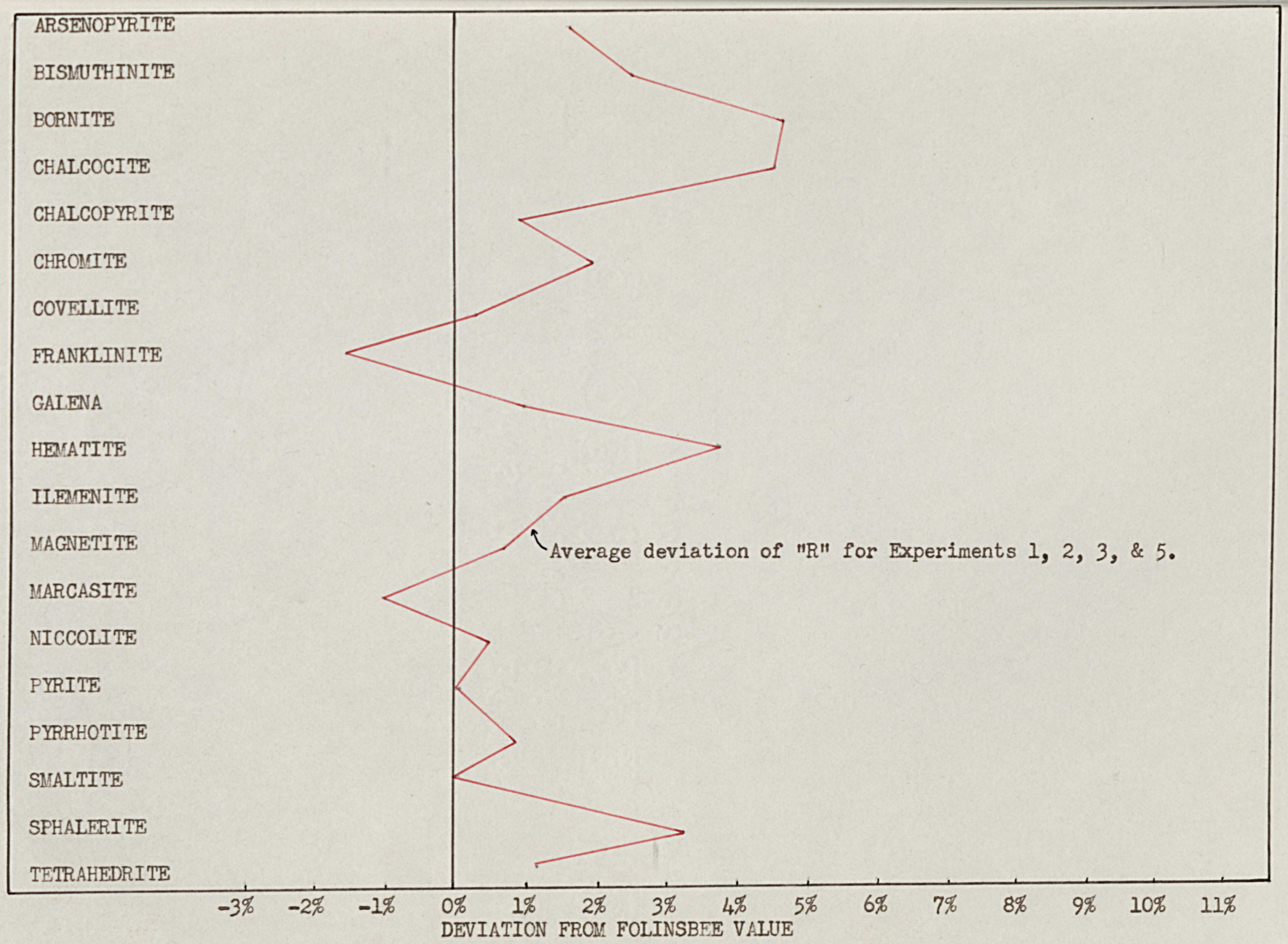

PLATE VI. Deviation Chart--Represents the deviation of the author's work from the Folinsbee values of reflectivity which are graphed as the zero percent line.

The use of a 10X ocular and a 4 mm. objective lens gave a magnification of approximately 470, which was probably too high to obtain good results considering that Moses (10) used a magnification of 120 diameters. The magnification for the remainder of the experiments was about 240. Folinsbee's results were obtained with a magnification of 350.

Average values fall, for the most part, within 3% of the values obtained by Folinsbee. (See Plates 3,4, and 5) If a static arrangement of equipment, i.e., the same light intensity, focal length, lenses, magnification, standard values, and amount of flare had been used in all experiments, the results would undoubtedly have been more consistent. The comparability of the results under these self-imposed conditions, however, speaks for itself. (See Table No. 1)

THE RELATION OF REFLECTIVITY AND ATOMIC NUMBER

Phillips (12: 461) has stated that reflectivity tends to increase with increasing atomic number. This theory, however, appears to be modified by the electron configurations and atomic volumes of the elements involved. Phillips theory was tested using Folinsbee's values of reflectivity and was found to hold true for the sulphides, tellurides, and selenides of the same mineral. When, however, the rule was applied to a series of the various sulphides, a great many exceptions were found. In seeking an explanation of this phenomenon, it was noticed that sulfur, selenium, and tellurium all occurred in Group VI-A of the periodic table. (Table No. 3) During the ensuing search for similar occurrences among the other elements, the

following relationship was discovered.

A relative increase in reflectivity with increasing atomic number can be traced in measuring the reflectivity of opaque, polished ore surfaces. This relationship, however, tends to hold true only for the minerals containing elements that have a similar electron configuration in their outer shells, i.e., those which occur in the same group (As, Sb, and Bi) or the same period (Fe, Co, and Ni) of the periodic table. Those elements occurring in the same group are more likely to exhibit a relative increase in reflectivity with increasing atomic number than those that are found in the same period. For the elements found in the same period, but in widely separated groups, such as Mn and As, the relationship does not apply. If, however, the groups are closely associated, as are the groups including iron, cobalt, nickel, and copper, the theory seems to be justified. Relative values are seldom obtained for the elements that occur in neither the same period or group.

The application of this theory also seems to require modification with respect to the atomic volume of the elements involved. Those elements occurring in a "favourable position" in the periodic chart as outlined above, such as mercury, zinc, and cadmium, and possessing widely differing atomic volumes do not exhibit comparable relationships. Table No. 4 sets forth the reflectivities obtained by Folinsbee (5: 432) with respect to changes in atomic number as worked out by the author. Minerals of similar composition are grouped together to make the relationships involved more easily understood. Table No. 4 should be studied in conjunction with Tables No. 2 and No. 3 to substantiate the above discussion.

ATOMIC STRUCTURE OF THE ELEMENTS

Element	Symbol	Electron Configuration[1]	Atomic Number[2]	Atomic Volume[3]
Antimony	Sb	2-3	51	18.40
Arsenic	As	2-3	33	13.10
Bismuth	Bi	2-3	83	21.30
Cadmium	Cd	2-0	48	13.00
Cobalt	Co	7-2	27	6.60
Copper	Cu	10-1	29	7.09
Iron	Fe	6-2	26	7.10
Lead	Pb	2-2	82	18.27
Manganese	Mn	5-2	25	7.39
Mercury	Hg	2-0	80	14.81
Nickel	Ni	8-2	28	6.59
Oxygen	O	2-4	8	.....
Selenium	Se	2-4	34	16.40
Silver	Ag	10-1	47	10.28
Sulfur	S	2-4	16	15.50
Tellurium	Te	2-4	52	20.50
Zinc	Zn	2-0	30	9.17

1. Number of electrons in the last two electron shells. (14: 570)
2. Atomic Number (14: 573)
3. Atomic Volume (18: 20)

TABLE NO. 2

VII-B	VIII-B			I-B	II-B	III-A	IV-A	V-A	VI-A	VII-A
						5 B	6 C	7 N	8 O	9 F
						13 Al	14 Si	15 P	16 S	17 Cl
25 Mn	26Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Hr	33 As	34 Se	35 Br
43 Ma	44Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I
75 Re	760s	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85

TABLE NO. 3. Portion of Mendeleef's Modified Periodic Table (14: 573)

THE RELATIONSHIP BETWEEN ATOMIC NO. AND REFLECTIVITY

Mineral	Chemical Formula	Atomic Number of differing element	Folinsbee Value of "R"
Altaite	PbTe	52	63.2
Clausthalite	PbSe	34	50.4
Galena	PbS	16	42.4
Chalcocite	Cu_2S	29	32.3
Argentite	Ag_2S	47	36.1
Argentite	Ag_2S	47	36.1
Hessite	Ag_2Se	52	39.0
Coloradoite	HgTe	80	37.7
Altaite	PbTe	52	63.2
Bismuthinite	Bi_2S_3	26	41.0
Gaunojuatite	Bi_2Se_2	34	46.2
Orpiment	As_2S_3	33	21.9
Bismuthinite	Bi_2S_3	83	41.0
Marcasite	FeS_2	16	51.5
Loellingite	$FeAs_2$	33	53.8
Niccolite	NiAs	33	52.6
Millerite	NiS	16	54.5
Proustite	Ag_3AsS_3	33	29.9
Pyargyrite	Ag_3SbS_3	51	30.9
Alabandite	MnS	25	23.9
Troilite	FeS	26	37.5
Millerite	NiS	28	54.5
Greenockite	CdS	48	17.0
Sphalerite	ZnS	30	17.8
Cuprite	Cu_2O	8	27.7
Chalcocite	Cu_2S	16	32.3
Cinnabar	HgS	80	26.3
Galena	PbS	82	42.4
Covellite	CuS	29	15.1
Sphalerite	ZnS	30	17.8
Realgar	AsS	33	18.7

TABLE NO. 4

CONCLUSION

The reflectivity of an ore mineral is a measureable constant that can be used to supplement other methods for simple, rapid, identification of isotropic ore minerals. This constant may be determined with accuracy to within 3% on well polished specimans by using the simplified apparatus as outlined in this report. Although the accuracy of the observed values as determined by the author may only restrict the identification to ten different minerals, these minerals have other easily determined and widely differing characteristics that may be utilized to aid the process of identification.

Reflectivity may be computed from the index of refraction according to the Fresnel equation or from the molecular refractivity according to the Lorenz-Lorentz equation. It also bears an important relationship to the atomic structure of the elements contained in the mineral. Reflectivity tends to increase with increasing atomic number. This relationship, however, seems to be modified by the position on the periodic table, the electron configuration in the outer shells, and the atomic volume.

In the author's opinion, further investigation of the subject should prove both fruitful and interesting. For this reason, all sources of information, methods of calculation, and individual results of the work are contained in the appendices of this report.

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APPENDIX

TABULATED DATA FOR EXPERIMENT NO. I

Microscope: Spencer No. 46 Metallurgical

Ocular: 10X

Objective: 8 mm. Diaphragm: Open

Flare: 2% Pyrite Standard: 51%

k (constant): 1.11 Formula: $(M-F)\ k = R^1$

Mineral Name	Polish[2]	Anisotropism[3]	M	M-F	R	Folinsbee Value
Arsenopyrite	G	S	50.0	48.0	53.4	52.4
Bismuthinite	F	S	41.0	39.0	42.9	41.0
Bornite	G	I-W	28.5	26.5	29.5	23.8
Chalcocite	G	W	35.0	33.0	36.7	32.3
Chalcopyrite	G	W	41.6	39.6	44.0	43.2
Chromite	F	I	19.5	17.5	19.4	12-26
Copper	G	I	53.0	51.0	56.6	72.8
Covellite	G	S	16.5	14.5	16.1	15.1
Cuprite	P	D	29.0	27.0	30.0	27.7
Franklinite	P	I	18.6	16.6	18.5	18.9
Galena	G	I	40.5	38.5	42.8	42.4
Hematite	P	W	30.0	28.0	31.1	27.2
Ilemenite	F	D	27.0	25.0	27.8	19.4
Magnetite	P	I	22.0	20.0	22.2	21.1
Marcasite	F	S	48.0	46.0	51.2	51.5
Niccolite	G	S	49.0	47.0	52.3	52.6
Pyrite	G	I	51.0	49.0	54.5	54.5
Pyrrhotite	F	S	40.0	38.0	42.2	39.9
Smaltite	F		48.0	46.0	51.2	54.6
Sphalerite	G	I	23.3	21.3	23.7	17.8
Tetrahedrite	F	I	31.0	29.0	32.2	31.2

1. M indicates meter reading, F indicates flare, and R indicates reflectivity in percent.

2. Polish is reported on an arbitrary basis as good (G), fair (F), or poor (P).

3. Anisotropism is reported as in Folinsbee (5: 432-436); I-isotropic W-weak, D-distinct, S-strong.

TABULATED DATA FOR EXPERIMENT NO. II

Microscope: Spencer No. 46 Metallurgical

Ocular: 10X

Objective: 8 mm. Diaphragm: Open

Flare: 1.5% Pyrite Standard: 50%

k (constant): 1.123 Formula: (M-F) k = R

Mineral Name	Polish	Anisotropism	M	M-F	R	Folinsbee Value
Arsenopyrite	G	S	50.0	48.5	54.5	52.4
Bismuthinite	F	S	42.1	40.6	44.6	41.0
Bornite	G	I-W	28.0	26.5	29.1	23.8
Chalcocite	G	W	35.0	33.5	37.6	32.3
Chalcopyrite	G	W	40.0	38.5	43.3	43.2
Chromite	F	I	19.0	17.5	19.7	12-26
Copper	G	I	55.0	53.5	60.1	72.8
Covellite	G	S	15.5	14.0	15.4	15.1
Cuprite	P	D	25.0	23.5	26.4	27.7
Franklinite	P	I	16.0	14.5	16.3	18.9
Galena	G	I	40.0	38.5	42.1	42.4
Hematite	P	W	27.0	25.5	28.6	27.2
Ilemenite	F	D	20.0	18.5	20.8	19.4
Magnetite	P	I	20.0	18.5	20.8	21.1
Marcasite	F	S	47.0	45.5	51.2	51.5
Niccolite	G	S	50.0	48.5	54.5	52.6
Pyrite	G	I	50.0	48.5	54.5	54.5
Pyrrhotite	F	S	38.0	36.5	41.0	39.9
Smaltite	F		50.0	48.5	54.5	54.6
Sphalerite	G	I	21.0	19.5	21.9	17.8
Tetrahedrite	F	I	31.0	29.5	33.2	31.2

TABULATED DATA FOR EXPERIMENT NO. III

Microscope: Spencer No. 46 Metallurgical

Ocular: 10X

Objective: 8 mm. Diaphragm: One-half open

Flare: 0% Pyrite Standard: 33%

k (constant): 1.65 Formula: (M-F) k = R

Mineral Name	Polish	Anisotropism	M	M-F	R	Folinsbee Value
Arsenopyrite	G	S	33.0	33.0	54.5	52.4
Bismuthinite	F	S	27.2	27.2	43.6	41.0
Bornite	G	I-W	16.0	16.0	26.4	23.8
Chalcocite	G	W	22.3	22.3	36.8	32.3
Chalcopyrite	G	W	27.0	27.0	44.5	43.2
Chromite	F	I	9.5	9.5	14.9	12-26
Copper	G	I	28.0	28.0	44.5	72.8
Covellite	G	S	8.1	8.1	13.4	15.1
Cuprite	P	D	16.0	16.0	26.4	27.7
Franklinite	P	I	10.5	10.5	17.6	18.9
Galena	G	I	27.7	27.7	45.7	42.4
Hematite	P	W	20.2	20.2	33.4	27.2
Ilemenite	F	D	13.5	13.5	22.3	19.4
Magnetite	P	I	15.3	15.3	25.2	21.1
Marcasite	F	S	28.6	28.6	47.2	51.5
Niccolite	G	S	32.0	32.0	52.8	52.6
Pyrite	G	I	33.0	33.0	54.5	54.5
Pyrrhotite	F	S	24.5	24.5	40.5	39.9
Smaltite	F		33.0	33.0	54.5	54.6
Sphalerite	G	I	11.6	11.6	19.1	17.8
Tetrahedrite	F	I	22.4	22.4	32.4	31.2

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TABULATED DATA FOR EXPERIMENT NO. IV

Microscope: Leitz Wetzler

Ocular: 10X

Objective: 4 mm.

Diaphragm: Open

Flare: 6%

Pyrite Standard: 60.5%

k (constant): 1

Formula: (M-F) k = R

Mineral Name	Polish	Anisotropism	M	M-F	R	Folinsbee Value
Arsenopyrite	G	S	59.0	53.0	53.0	52.4
Bismuthinite	F	S	48.5	42.5	42.5	41.0
Bornite	G	I-W	39.5	33.5	33.5	23.8
Chalcocite	G	W	46.0	40.0	40.0	32.3
Chalcopyrite	G	W	52.5	46.5	46.5	43.2
Chromite	F	I	27.0	21.0	21.0	12-26
Copper	G	I	61.0	55.0	55.0	72.8
Covellite	G	D	22.9	16.9	16.9	15.1
Cuprite	P	D	20.0	14.0	14.0	27.7
Franklinite	P	I	32.0	26.0	26.0	18.9
Galena	G	I	53.0	47.0	47.0	42.4
Hematite	P	W	44.0	38.0	38.0	27.2
Ilemenite	F	D	35.0	29.0	29.0	19.4
Magnetite	P	I	34.0	28.0	28.0	21.1
Marcasite	F	S	57.5	51.5	51.5	51.5
Niccolite	G	S	61.5	55.5	55.5	52.6
Pyrite	G	I	60.5	54.5	54.5	54.5
Pyrrhotite	F	S	52.5	46.5	46.5	39.9
Smaltite	F		62.0	56.0	56.0	54.6
Sphalerite	G	I	34.0	28.0	28.0	17.8
Tetrahedrite	F	I	44.8	38.8	38.8	31.2

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TABULATED DATA FOR EXPERIMENT NO. V

Microscope: Spencer No. 46 Metallurgical

Ocular: 10X

Flare: 3%

Diaphragm: Open

k (constant): 1.16

Pyrite Standard: 50%

Objective: 8mm.

Formula: (M-F) k = R

Mineral Name	Polish	Anisotropism	M	M-F	R	Folinsbee Value
Arsenopyrite	G	S	49.5	46.5	54.0	52.4
Bismuthinite	F	S	40.0	37.0	43.8	41.0
Bornite	G	I-W	25.5	22.5	26.1	23.8
Chalcocite	G	W	35.0	32.0	37.0	32.3
Chalcopyrite	G	W	41.0	38.0	44.0	43.2
Chromite	F	I	20.0	17.0	19.7	12-26
Copper	G	I	51.5	48.5	56.2	72.8
Covellite	G	S	16.6	13.6	15.8	15.1
Cuprite	P	D	25.0	23.0	26.6	27.7
Franklinite	P	I	17.8	14.8	17.2	18.9
Galena	G	I	40.0	37.0	43.0	42.4
Hematite	P	W	28.6	25.6	29.7	27.2
Ilemenite	F	D	20.5	17.5	20.3	19.4
Magnetite	P	I	20.5	17.5	20.3	21.1
Marcasite	F	S	48.0	45.0	52.0	51.5
Niccolite	G	S	49.0	46.0	53.4	52.6
Pyrite	G	I	50.0	47.0	54.5	54.5
Pyrrhotite	F	S	38.0	35.0	40.6	39.9
Smaltite	F		50.0	47.0	54.5	54.6
Sphalerite	G	I	21.9	18.9	21.9	17.8
Tetrahedrite	F	I	31.0	28.0	32.5	31.2